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Guidelines for Using Eastcoast 2001 Database of Tidal Constituents within Western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea

by Ann Y. Mukai, Joannes J. Westerink, and Richard A. Luettich

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the Eastcoast 2001 computed database of tidal elevation and velocity constituents. This database was developed to allow surface-water elevation and currents to be quickly and easily defined in open waters within the Western North Atlantic Tidal (WNAT) domain. The WNAT domain encompasses the Western North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea. The Eastcoast 2001 database defines the computed elevation and velocity amplitude and phase for the O_1, K_1, Q_1, M_2, S_2, N_2, and K_2 astronomical tidal constituents as well as the steady, M_4 and M_6 overtides. This CHETN summarizes the development of the Eastcoast 2001 tidal constituent database, presents global, basin-specific and site-specific error estimates, and discusses exactly what is computed, where it can be applied, and how it can and should be used. Limitations of the database are also described.

BACKGROUND: Coastal ocean tidal models are used to define navigable depths and currents in nearshore regions, to assess pollutant and/or sediment movement on the continental shelf, and to evaluate coastal inundation. The hydrodynamics of coastal tides are difficult to predict due to various complexities including irregular coastlines, intricacies of the ocean floor, and the interaction of astronomical tides and numerous nonlinearly generated overtides and compound tides. Since the tidal problem cannot be directly solved analytically, numerical models are developed to evaluate sea surface elevations and currents.

A successful strategy to enhance the accuracy of coastal ocean circulation models has been the use of increasingly larger computational domains. In recent studies, accurate tidal predictions are correlated to large computational domains, such as the Western North Atlantic Tidal (WNAT) model domain (Westerink, Luettich, and Scheffner 1993; Westerink, Luettich, and Muccino 1994; Westerink, Luettich, and Pourtaheri 2000; Blain, Westerink, and Luettich 1994, 1998). The WNAT domain, shown in Figure 1, encompasses the Western North Atlantic Ocean, Gulf of Mexico, and the Caribbean Sea. The domain has an eastern open ocean boundary along the 60-deg west meridian, where the bathymetry is located almost entirely in the deep ocean. This boundary is situated such that an accurate set of boundary conditions can be specified. The 60-deg west meridian was chosen because the open ocean boundary is geometrically simple and is not within a resonant basin such as the Gulf of Mexico. Furthermore, the boundary is mostly in the deep Atlantic where tides vary more gradually than on the shelf and nonlinear overtide and compound tide species are minimal.

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14. ABSTRACT
This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the Eastcoast 2001 computed database of tidal elevation and velocity constituents. This database was developed to allow surface-water elevation and currents to be quickly and easily defined in open waters within the Western North Atlantic Tidal (WNAT) domain. The WNAT domain encompasses the Western North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea. The Eastcoast 2001 database defines the computed elevation and velocity amplitude and phase for the O1, K1, Q1, M2, S2, N2, and K2 astronomical tidal constituents as well as the steady, M4 and M6 overtides. This CHETN summarizes the development of the Eastcoast 2001 tidal constituent database, presents global, basin-specific and site-specific error estimates, and discusses exactly what is computed, where it can be applied, and how it can and should be used. Limitations of the database are also described.

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Figure 1. WNAT domain definition

The key to using large computational domains such as the WNAT domain is to define graded unstructured grids that provide the necessary level of grid resolution on a localized basis. Deep ocean waters only require a relatively coarse level of resolution since tidal response functions vary slowly in space while shallow coastal waters require a much higher level of grid resolution since tides vary much more rapidly than in deep waters. The WNAT domain has been the basis of a series of tidal constituent database computations over the past decade including the Eastcoast 1991 (Westerink, Luettich, and Scheffner 1993; Westerink, Luettich, and Muccino 1994), Eastcoast 1995, and Eastcoast 2001 (Mukai et al. 2001) databases. Each database has been developed by building progressively better resolved grids, defining more accurate coastlines, including more islands and using improved bathymetric databases. The resolution improvements have been achieved by placing more nodes as well as by placing these nodes more strategically using more sophisticated node placement algorithms. The hydrodynamic numerical model used in all the WNAT tidal database computations is ADCIRC-2DDI, the

depth-integrated option of the two- and three-dimensional fully nonlinear hydrodynamic code ADCIRC (Luettich, Westerink, and Scheffner 1992; Additional information available on the World Wide Web at *http://www.marine.unc.edu/C_CATS/adcirc/adcirc.htm*).

The earliest WNAT tidal database, Eastcoast 1991, applied 19,858 nodes and 36,653 elements with element sizes varying from 7 km at the coastline to approximately 140 km in the deep ocean. The Eastcoast 1991 bathymetry was constructed from the ETOPO5 (National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, CO 80303-3328, 1988; *http://edcwww.cr.usgs.gov/glis/hyper/guide/etopo5*) bathymetric database which defines bathymetry on a coarse resolution 5-min by 5-min grid and extends over all the world oceans. Eastcoast 1991 had average tidal constituent errors in amplitude between 18.2 percent and 45.3 percent, and average errors in phase between 8.3 deg and 27.5 deg for predictive WNAT tidal computations driven by the K_1, O_1, Q_1, M_2, S_2, N_2, and K_2 constituents.

The most recent tidal database, Eastcoast 2001, applies 254,629 nodes and 492,182 elements within the WNAT domain. The Eastcoast 2001 grid is shown in Figure 2. Resolution varies from a defined minimum element size generally ranging from 1 to 4 km along the land boundaries to a defined maximum element size equal to 25 km in the deep ocean. The Eastcoast

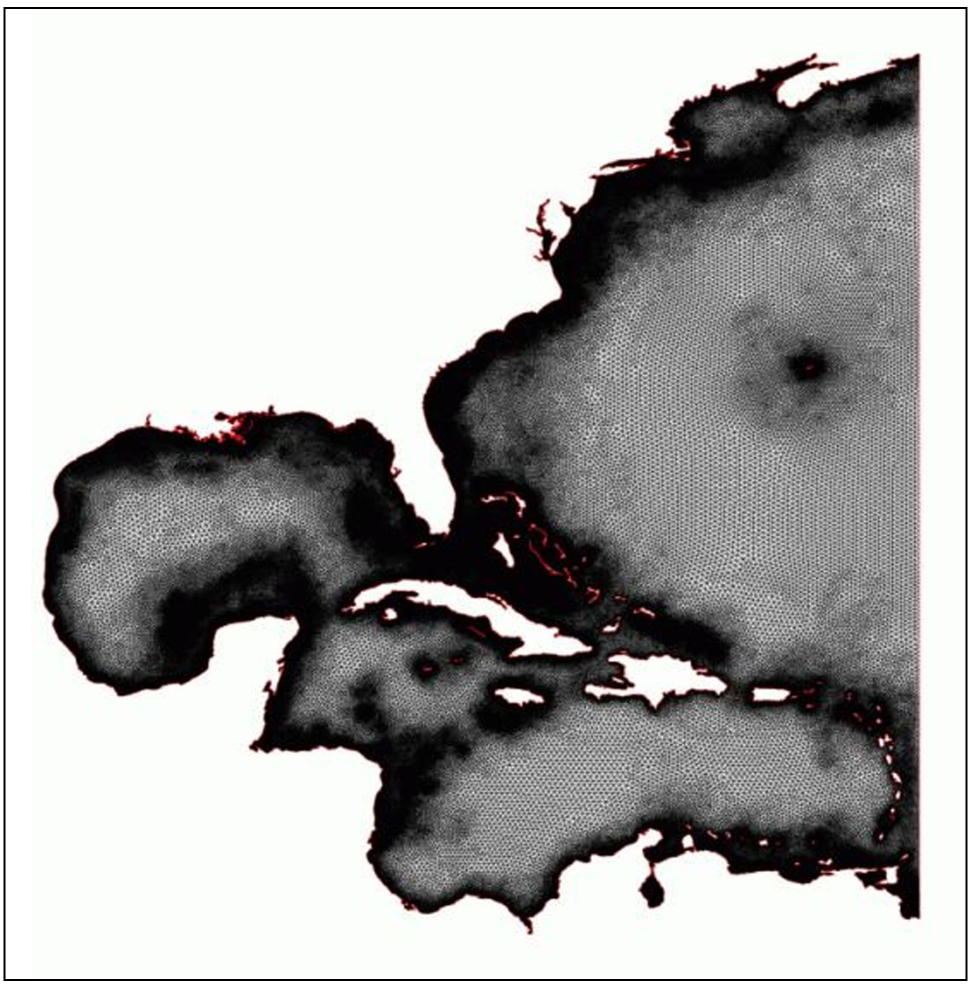

Figure 2. Eastcoast 2001 finite element grid

2001 grid significantly improves the ability to propagate tides as indicated by measures such as the number of nodes per wavelength as well as the Topographic Length Scale criterion which relates grid size, bathymetric gradient and depth (Mukai et al., in preparation). The coastline boundaries for the Eastcoast 2001 grid were updated with the Defense Mapping Agency's World Vector Shoreline database (Soluri and Woodson 1990; data obtained from the National Geophysical Data Center, World Wide Web page accessed on 25 February 2000, *http://rimmer.ngdc.noaa.gov/coast*).

Eastcoast 2001 depths were defined using three bathymetric databases including: ETOPO5 which can provide bathymetric values throughout the WNAT domain; the Digital Nautical Charts (DNC) bathymetric database, produced by the National Imagery and Mapping Agency (U.S. Department of Defense, National Imagery Mapping Agency, Digital Nautical Chart, Washington DC 1999) which provides bathymetry throughout most of the WNAT domain with significantly more accuracy than the ETOPO5 database; and the NOS raw sounding bathymetric database (NOS Hydrographic Survey Digital Database, CD-ROM set, Vol. 1, Version 3.3 1997; additional information is available on the World Wide Web at *http://www.ngdc.noaa.gov/mgg/fliers/97mgg02.html*) which represents the raw soundings tracks over predominantly U.S. continental shelf waters and is considered the most reliable of the three bathymetric databases. The ETOPO5 and DNC databases significantly differ in certain important regions such as the Great Bahama Bank for which ETOPO5 indicates depths of hundreds of meters whereas DNC indicates depths on the order of meters. This difference dramatically influences the exchange between the Atlantic Ocean and the Gulf of Mexico. A comparison between the DNC and NOS data indicates that these sets are similar to each other.

The final bathymetry for the Eastcoast 2001 grid, shown in Figure 3, was defined using a priority/availability system. In areas where NOS values are available, these values are used and applied to the finite element grid using a gathering/averaging procedure. The secondary database used is the DNC, and the third is ETOPO5 if no other sources are available. Both the DNC and ETOPO5 bathymetric values are directly interpolated onto the Eastcoast 2001 grid.

The Eastcoast 2001 domain was forced on the 60-deg west meridian open boundary with O_1, K_1, Q_1, M_2, N_2, S_2, and K_2 tidal amplitudes and phases interpolated onto the open ocean boundary nodes using data from Le Provost 1995 global model (Le Provost et al. 1998). Le Provost created a worldwide ocean tidal database from a finite element hydrodynamic model in 1994, designated FES94.1 (Le Provost, Bennett, and Cartwright 1995). In 1995, Le Provost revised FES94.1 by assimilating a satellite altimeter-derived data set, thus creating FES95.2. FES95.2 has better accuracy than FES94.1 because of corrections to major constituents by TOPEX/POSEIDON mission data assimilation and because of the increase in the number of constituents in the model. It is noted that Le Provost's database values had to be extrapolated for portions of the Eastcoast 2001 open ocean boundary lying on the continental shelf in the vicinity of Nova Scotia and Venezuela since Le Provost's databases do not provide complete coverage in these areas. Simply applying the nearest available FES95.2 value across the stretches of the continental shelf not covered by FES95.2 led to the formation of unphysical and unstable eddies on the shelf off Venezuela. Zero normal flow specified boundary conditions were applied to all coastal and island boundaries. Tidal potential amplitudes for the seven forcing constituents were specified. Tidal potential consists of lateral gravitational traction forces, which originate from

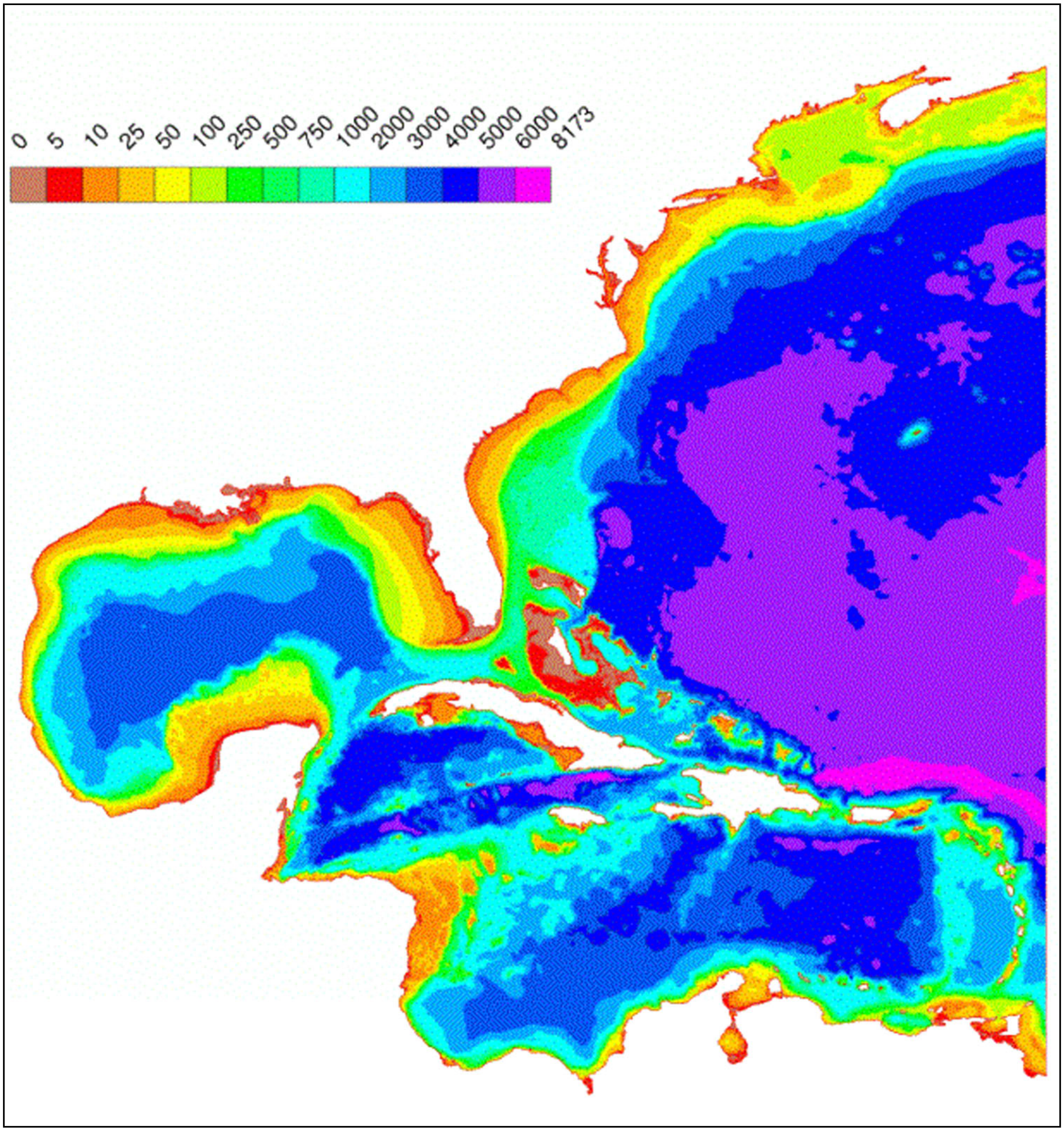

Figure 3. Eastcoast 2001 composite bathymetry in meters relative to the geoid

the sun and moon gravitational fields and force the tides as body forcing functions. It is necessary to specify these forces due to the large size of the WNAT domain and resonant behavior of the Gulf of Mexico and Caribbean Sea. Tidal potential forcing functions are entirely deterministic and can be accurately specified. Earth elasticity factors, which reduce the magnitude of the tidal potential forcing due to Earth tides, ranging between 0.693 to 0.736 were used instead of the theoretical value of 0.69 (Hendershott 1981).

The Eastcoast 2001 database can be used to directly evaluate surface-water elevation and current due to tides at locations within the bounds of the WNAT database domain. The database can also be used to drive smaller regional hydrodynamic models that incorporate a greater level of geometric, bathymetric, and/or hydrodynamic detail than the Eastcoast 2001 model itself. Applying computed values from the Eastcoast 2001 tidal constituent database as the open ocean forcing for a regional model will typically result in an accurate and physically correct set of forcing functions on the open ocean boundary of the smaller model.

EASTCOAST 2001 VALIDATION AND ERROR ESTIMATES: One-hundred-and-one measurement tidal elevation stations with high quality observational data in harmonic constituent form were selected for the Eastcoast 2001 model validation. These stations are scattered mostly along the coastlines and continental shelf as is shown in Figure 4. These 101 stations are used to

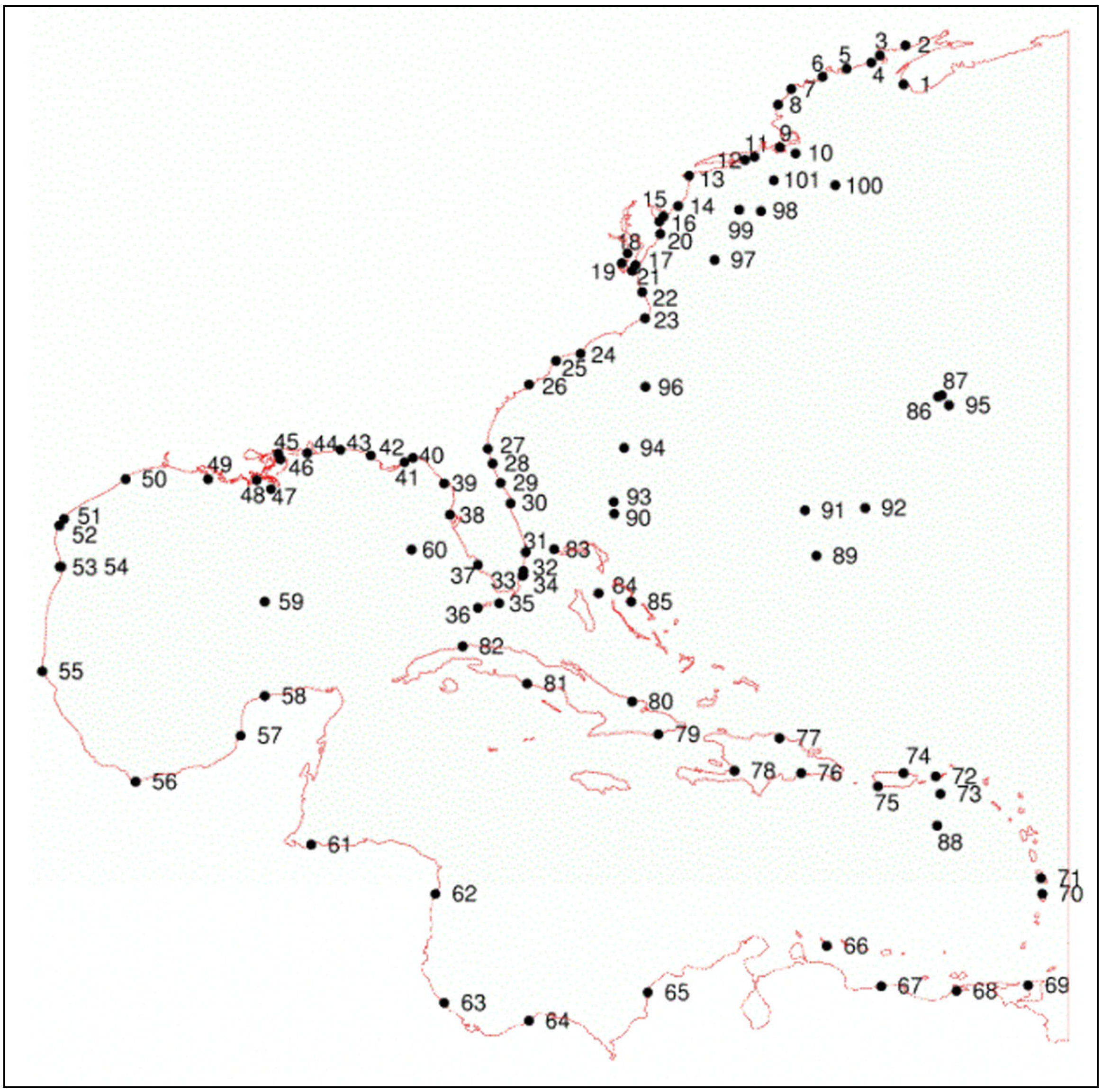

Figure 4. The 101 elevation measurement stations defined in WNAT domain

validate the Eastcoast 2001 harmonic tidal database values by comparing computed harmonically decomposed tidal elevation constituents with measured harmonically analyzed published field data. Published measured elevation harmonic constituent data is derived from long-term records of sea surface elevation. The measured station data are obtained from several sources: International Hydrographic Organization (IHO) Tidal Constituent Bank, 1991; U.S. Geological Survey, 1984; Reid and Whitaker 1981; the National Ocean Survey/Service (NOS) (NOS World Wide Web page: *http://co-ops.nos.noaa.gov/data_retrieve.shtml?input_code=100201001har*, Accessed on May 2, 2001), and the National Oceanographic and Atmospheric Administration (NOAA). Stations are listed in Table 1. Stations 1-34 lie along the Atlantic coastline; stations 35-60 and 82 are located in the Gulf of Mexico; stations 61-71,73,75,76,78,79,81, and 88 lie in the Caribbean Sea; and stations 72,74,77,80,83-87, and 89-101 are scattered in the deep Atlantic Ocean or near small islands in the Atlantic.

Most of these recording stations are located in open waters or in areas relatively accessible to the adjacent open ocean. A careful study of each station's location has been conducted to ensure that the stations closely represent the open water conditions that are simulated in the computations. Table 1 provides an overview of the location of each station by indicating if it is in the open ocean with no obstructions or the degree of constriction to the adjacent open waters. If the stations have flow partially impeded, the width of the opening and length of the path between open water and the recording station are noted. Because small inlets were typically not included in the computational domain and grid, it is important that stations do not lie too far away from open water and/or behind highly dissipative lateral or vertical constrictions. All stations selected represent as closely as possible the adjacent open water tidal elevation values.

The Eastcoast 2001 computed harmonic constituents compare well with measurements throughout the domain. The reliability of the computed tidal values was evaluated by comparing computed values at the 101 measurement stations for the seven astronomical constituents to available measured elevation field data. Figures 5 through 8 present the computed versus measured amplitude and phase for the O_1, K_1, Q_1, M_2, S_2, N_2, and K_2 constituents of four representative measured data stations throughout the WNAT domain. Each of the seven tidal constituents has a corresponding symbol found in the legend to the right of the plots. Some stations have two sets of constituent symbols. The data plotted in red are found on every plot and represent the basic set of IHO, NOAA, and older NOS values. The blue set of symbols shows updated NOS field measurements. Each graph has a solid diagonal line with a one-to-one ratio which represents a no error line, and two sets of dashed lines corresponding either to 5 and 10 percent amplitude error or 10 and 20-deg phase difference.

Ideally, plots of the tidal symbols will fall on the one-to-one ratio line, indicating that the simulated values exactly match the field values. The vast majority of the results fall within the 10 percent amplitude and 20-deg phase error range or better, and most of the dominant tidal constituent in each region can be found within the 5 percent amplitude and 10-deg phase error range. Note that phase errors for some of the smaller tidal constituents such as the Q_1 and K_2 can be large at some stations such as sta 66 at Curacao Antilles and sta 68 at Cumana, Venezuela. However, the corresponding amplitudes are extremely small, which could account for the large phasing errors since smaller waves are more susceptible to phase misalignment in the harmonic decomposition of the measurement data.

Table 1
Station Locations, Data Sources, Distance from Open Water, and Width of Narrowest Connection to Open Water

Station	Station Name	Lat (deg)	Long (deg)	Source	Sub-Domain	Distance km (mi)	Width km (mi)
1	Yarmouth, Nova Scotia	43.833333	-66.116667	IHO	Atlantic	4.47 (2.78)	1.61 (1.00)
2	St John, New Brunswick	45.266667	-66.050000	IHO	Atlantic	1.61 (1.00)	0.05 (0.03)
3	Eastport Passamaquoddy Bay, ME	44.903333	-66.985000	NOS	Atlantic	8.69 (5.40)	3.86 (2.40)
4	Cutler Naval Base, ME	44.641667	-67.296667	NOS	Atlantic	6.84 (4.25)	3.22 (2.00)
5	Bar Harbor, ME	44.400000	-68.200000	IHO[1]	Atlantic	8.85 (5.50)	6.61 (4.11)
6	Rockland, ME	44.105000	-69.101667	IHO[1]	Atlantic	6.44 (4.00)	8.05 (5.00)
7	Portland, ME	43.656667	-70.246667	NOS	Atlantic	5.31 (3.30)	0.90 (0.56)
8	Portsmouth, NH	43.080000	-70.741667	IHO	Atlantic	5.54 (3.44)	2.57 (1.60)
9	Woods Hole, MA	41.513333	-70.670000	IHO[1]	Atlantic	4.82 (3.00)	15.77 (9.80)
10	Nantucket Island, MA	41.286667	-70.095000	NOAA[1]	Atlantic	20.92 (13.00)	15.98 (9.93)
11	Block Island, RI	41.158333	-71.613333	NOS	Atlantic	--	--
12	Montauk, NY	41.050000	-71.966667	IHO[1]	Atlantic	25.11 (15.60)	21.40 (13.30)
13	Sandy Hook, NJ	40.468333	-74.011667	IHO[1]	Atlantic	6.44 (4.00)	8.53 (5.30)
14	Atlantic City, NJ	39.351667	-74.418333	IHO[1]	Atlantic	--	--
15	Cape May Ferry Terminal, NJ	38.968333	-74.960000	IHO[1]	Atlantic	4.82 (3.00)	17.38 (10.80)
16	Lewes, DE	38.781667	-75.120000	NOS	Atlantic	2.45 (3.94)	18.19 (11.30)
17	Kiptopeke, VA	37.166667	-75.988333	NOS	Atlantic	9.66 (6.00)	19.63 (12.20)
18	Windmill Point, VA	37.615000	-76.290000	NOS	Atlantic	--	--
19	Gloucester Point, VA	37.246667	-76.500000	NOS	Atlantic	11.27 (7.00)	3.59 (2.23)
20	Fishing Pier Ocean City, MD	38.323333	-75.085000	NOAA[1]	Atlantic	--	--
21	Chesapeake Bay, VA	36.966667	-76.113333	NOAA[1]	Atlantic	23.01 (14.30)	10.73 (6.67)
22	Duck Pier, NC	36.181667	-75.750000	NOAA[1]	Atlantic	--	--
23	Cape Hatteras Fishing Pier, NC	35.223333	-75.635000	NOS	Atlantic	--	--
24	Southport, NC	33.915000	-78.016667	IHO	Atlantic	4.88 (3.03)	1.93 (1.20)
25	Springmaid Pier, SC	33.655000	-78.918333	NOS	Atlantic	--	--
26	Charleston, SC	32.783333	-79.916667	IHO[1]	Atlantic	6.89 (4.28)	2.38 (1.48)
27	Mayport, FL	30.400000	-81.433333	IHO[1]	Atlantic	1.61 (1.00)	0.71 (0.44)
28	St. Augustine Beach, FL	29.856667	-81.263333	NOS	Atlantic	--	--
29	Daytona Beach (ocean), FL	29.146667	-80.963333	NOS	Atlantic	--	--
30	Canaveral Harbor Entrance, FL	28.408333	-80.600000	NOS	Atlantic	1.37 (0.85)	0.16 (0.10)
31	Lake Worth Pier, FL	26.611667	-80.033333	NOS	Atlantic	--	--
32	Haulover Pier N. Miami Beach, FL	25.903333	-80.120000	NOS	Atlantic	--	--

(Sheet 1 of 3)

[1] Sources were updated with current measured NOS data

Table 1 (Continued)

Station	Station Name	Lat (deg)	Long (deg)	Source	Sub-Domain	Distance km (mi)	Width km (mi)
33	Miami Harbour, FL	25.768333	-80.130000	IHO[1]	Atlantic	3.38 (2.10)	0.90 (0.56)
34	Virginia Key, FL	25.731667	-80.161667	NOS	Atlantic	--	--
35	Key Colony Beach, FL	24.718333	-81.018333	NOS	GOM	--	--
36	Key West, FL	24.550000	-81.800000	IHO[1]	GOM	--	--
37	Naples, FL	26.133333	-81.800000	IHO[1]	GOM	5.79 (3.60)	0.13 (0.08)
38	Clearwater Beach, FL	27.976667	-82.831667	NOS	GOM	--	--
39	Cedar Key, FL	29.133333	-83.031667	IHO[1]	GOM	--	--
40	St Marks Light, FL	30.066667	-84.183333	IHO[1]	GOM	--	--
41	Turkey Point, FL	29.915000	-84.511667	NOS	GOM	--	--
42	Alligator Bayou, FL	30.166667	-85.750000	IHO	GOM	9.53 (5.92)	(0.40) 0.25
43	Navarre Beach, FL	30.376667	-86.865000	NOS	GOM	--	--
44	Dauphin Island, AL	30.250000	-88.075000	NOS	GOM	0.26 (0.16)	5.23 (3.25)
45	Cat Island, MS	30.233333	-89.166667	IHO	GOM	7.08 (4.40)	10.14 (6.30)
46	Gulfport Harbor, Miss. Sound, MS	30.026667	-89.081667	NOS	GOM	--	--
47	Southwest Pass, LA	28.931667	-89.428333	IHO[1]	GOM	--	--
48	Grand Isle, East Point, LA	29.263333	-89.956667	NOS	GOM	42.16 (26.20)	18.99 (11.80)
49	Point au Fer, LA	29.286667	-91.750000	IHO	GOM	--	--
50	Galveston Pleasure Pier, TX	29.2850	-94.7883	NOS	GOM	--	--
51	Port Aransas, TX	27.825000	-97.058333	GOM	GOM	--	--
52	Corpus Christi, GOM, TX	27.5800	-97.2167	NOS	GOM	--	--
53	Port Isabel, Laguna Madre, TX	26.0600	-97.2150	NOS	GOM	8.05 (5.00)	0.40 (0.25)
54	South Padre Island, TX	26.066667	-97.150000	IHO	GOM	--	--
55	Ciudad Madero, Mexico	22.216667	-97.858333	GOM	GOM	13.04 (8.10)	0.48 (0.30)
56	Coatzacoalcos, Mexico	18.148333	-94.411667	IHO	GOM	--	--
57	Campeche, Mexico	19.833333	-90.533333	IHO	GOM	--	--
58	Progreso, Yucatan, Mexico	21.300000	-89.650000	IHO	GOM	--	--
59	Middle of GOM	24.766667	-89.650000	IHO	GOM	--	--
60	Florida Bank	26.700000	-84.250000	IHO	GOM	--	--
61	Puerto Cortes, Honduras	15.833333	-87.950000	IHO	Caribbean	--	--
62	Puerto Cabezas, Nicaragua	14.016667	-83.366667	IHO	Caribbean	--	--
63	Puerto Limon, Costa Rica	10.000000	-83.033333	IHO	Caribbean	--	--
64	Cristobal, Panama	9.350000	-79.916667	IHO	Caribbean	--	--
65	Cartagena, Colombia	10.383333	-75.533333	IHO	Caribbean	--	--
66	Curacao, Antilles	12.100000	-68.933333	IHO	Caribbean	--	--

(Sheet 2 of 3)

Table 1 (Concluded)

Station	Station Name	Lat (deg)	Long (deg)	Source	Sub-Domain	Distance km (mi)	Width km (mi)
67	La Guaira, Venezuela	10.616667	-66.933333	IHO	Caribbean	--	--
68	Cumana, Venezuela	10.450000	-64.166667	IHO	Caribbean	--	--
69	Port of Spain Trinidad and Tobago	10.650000	-61.516667	IHO	Caribbean	--	--
70	Castries, St Lucia	14.016667	-61.000000	IHO	Caribbean	--	--
71	Fort-de-France, Martinique	14.583333	-61.050000	IHO	Caribbean	--	--
72	St Thomas, Virgin Islands	18.333333	-64.933333	IHO[1]	Remote	--	--
73	Lime Tree Bay, St. Croix, VI	17.696667	-64.753333	NOS	Caribbean	--	--
74	San Juan, La Puntilla, Puerto Rico	18.461667	-66.116667	NOS	Remote	--	--
75	Magueyes Island, Puerto Rico	17.966667	-67.050000	IHO[1]	Caribbean	--	--
76	Ciudad, Dominican Republic	18.466667	-69.883333	IHO	Caribbean	--	--
77	Puerto Plato, Dominican Republic	19.750000	-70.683333	IHO	Remote	--	--
78	Port-au-Prince, Haiti	18.550000	-72.350000	IHO	Caribbean	--	--
79	Guantanomo Bay, Cuba	19.900000	-75.150000	IHO	Caribbean	--	--
80	Gibara, Cuba	21.100000	-76.116667	IHO	Remote	--	--
81	Casilda, Cuba	21.750000	-79.983333	IHO	Caribbean	--	--
82	Havana, Cuba	23.133333	-82.366667	IHO	GOM	--	--
83	Settlement Point Grand, Bahamas	26.710000	-78.996667	NOS	Remote	--	--
84	Nassau, Bahamas	25.083333	-77.350000	IHO	Remote	--	--
85	Eleuthera, Bahamas	24.766667	-76.150000	IHO	Remote	--	--
86	Ireland Island, Bermuda	32.316667	-64.833333	IHO	Remote	--	--
87	St Davids Islands, Bermuda	32.370000	-64.695000	IHO	Remote	--	--
88	East Caribbean Sea	16.533333	-64.883333	IHO	Caribbean	--	--
89	Atlantic Ocean	26.466667	-69.333333	IHO	Remote	--	--
90	Atlantic Ocean	28.016667	-76.783333	IHO	Remote	--	--
91	Atlantic Ocean	28.133333	-69.750000	IHO	Remote	--	--
92	Atlantic Ocean	28.233333	-67.533333	IHO	Remote	--	--
93	Atlantic Ocean	28.450000	-76.800000	IHO	Remote	--	--
94	Atlantic Ocean	30.433333	-76.416667	IHO	Remote	--	--
95	Atlantic Ocean near Bermuda	32.016667	-64.433333	IHO	Remote	--	--
96	Atlantic Ocean	32.683333	-75.616667	IHO	Remote	--	--
97	Atlantic Ocean	37.366667	-73.083333	IHO	Remote	--	--
98	Atlantic Ocean	39.166667	-71.366667	IHO	Remote	--	--
99	Atlantic Ocean	39.216667	-72.166667	IHO	Remote	--	--
100	Atlantic Ocean	40.116667	-68.633333	IHO	Remote	--	--
101	Atlantic Ocean	40.300000	-70.900000	IHO	Remote	--	--

(Sheet 3 of 3)

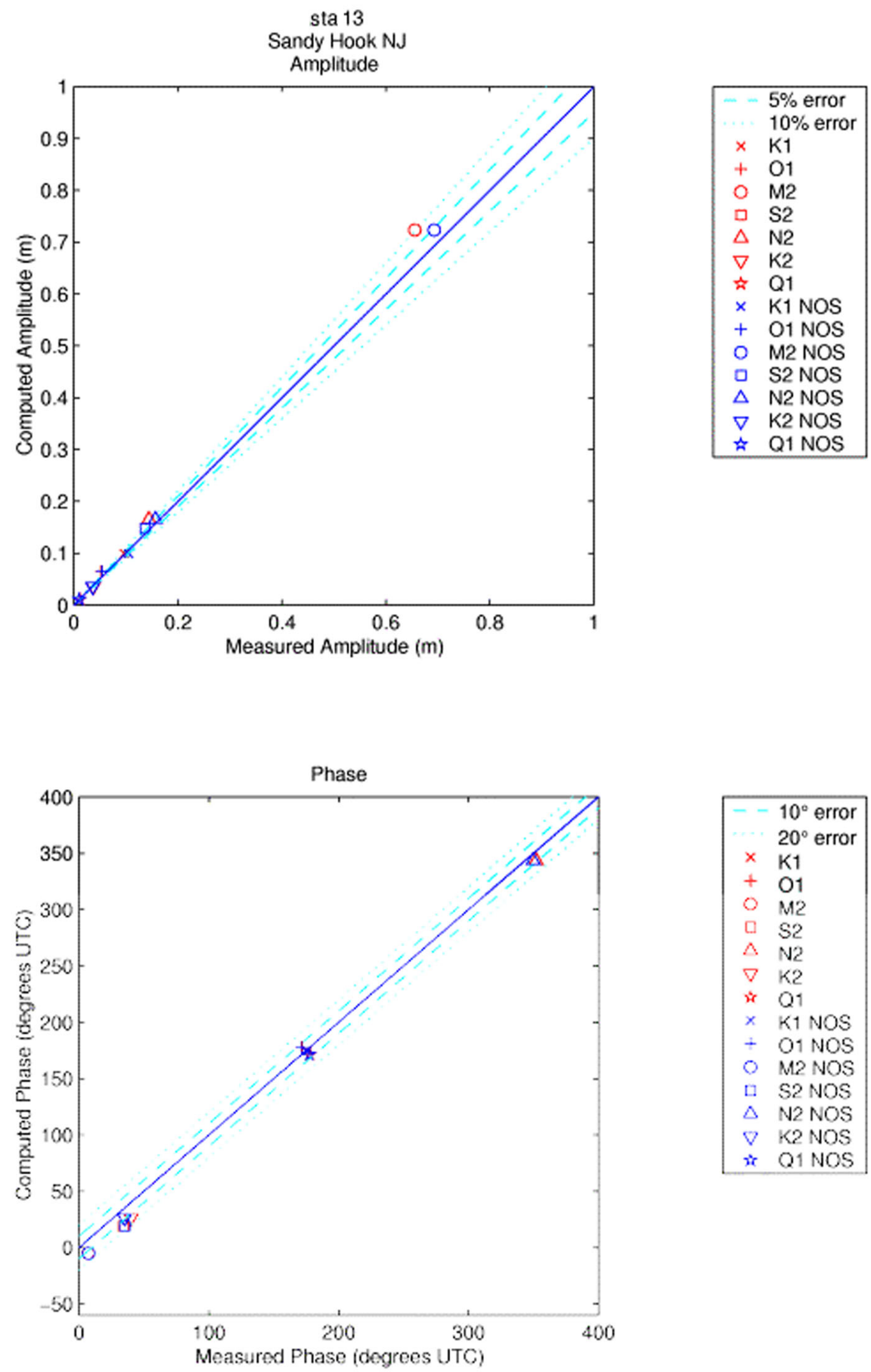

Figure 5. Computed versus measured harmonic constituents at sta 13

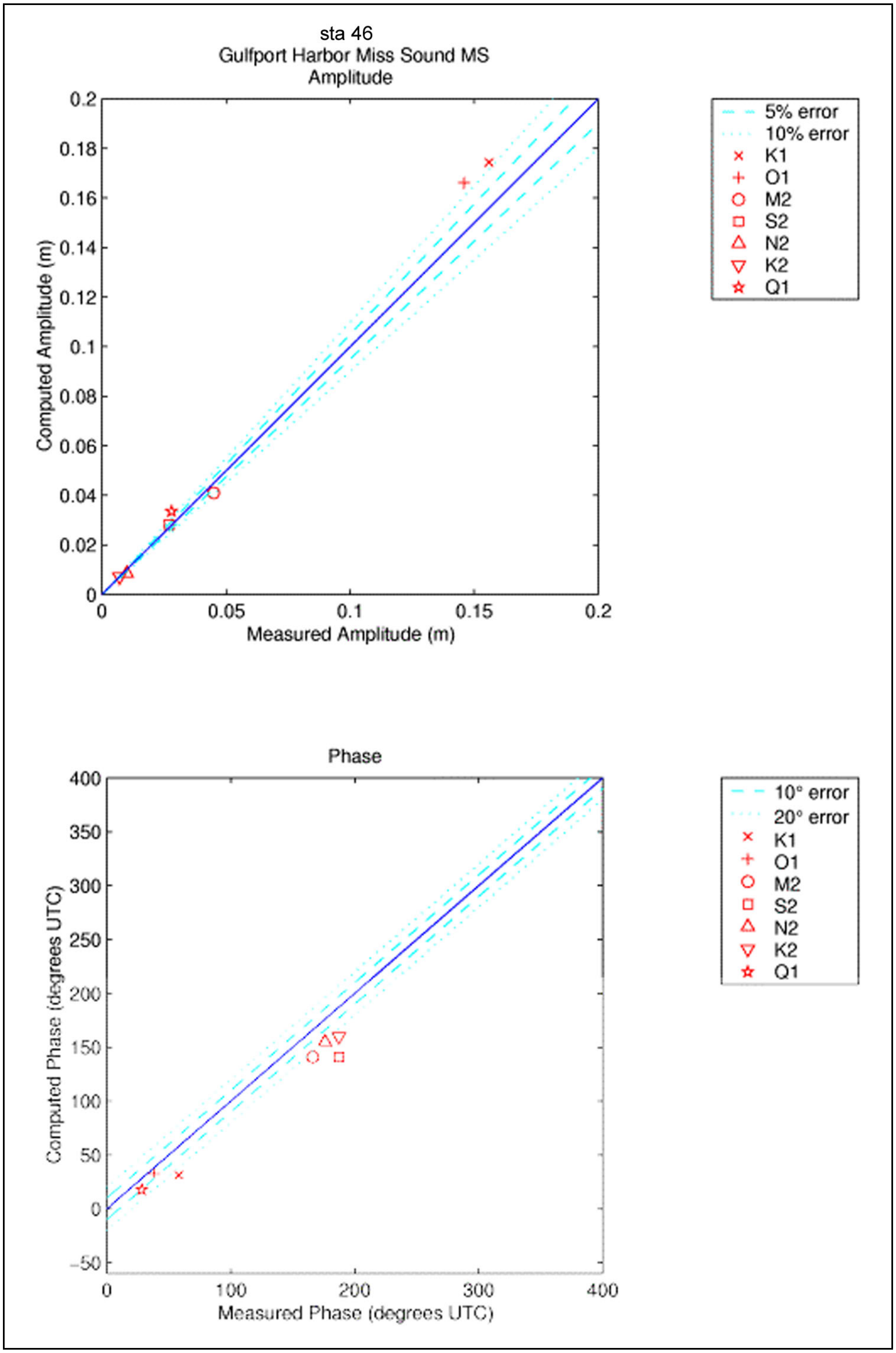

Figure 6. Computed versus measured harmonic constituents at sta 46

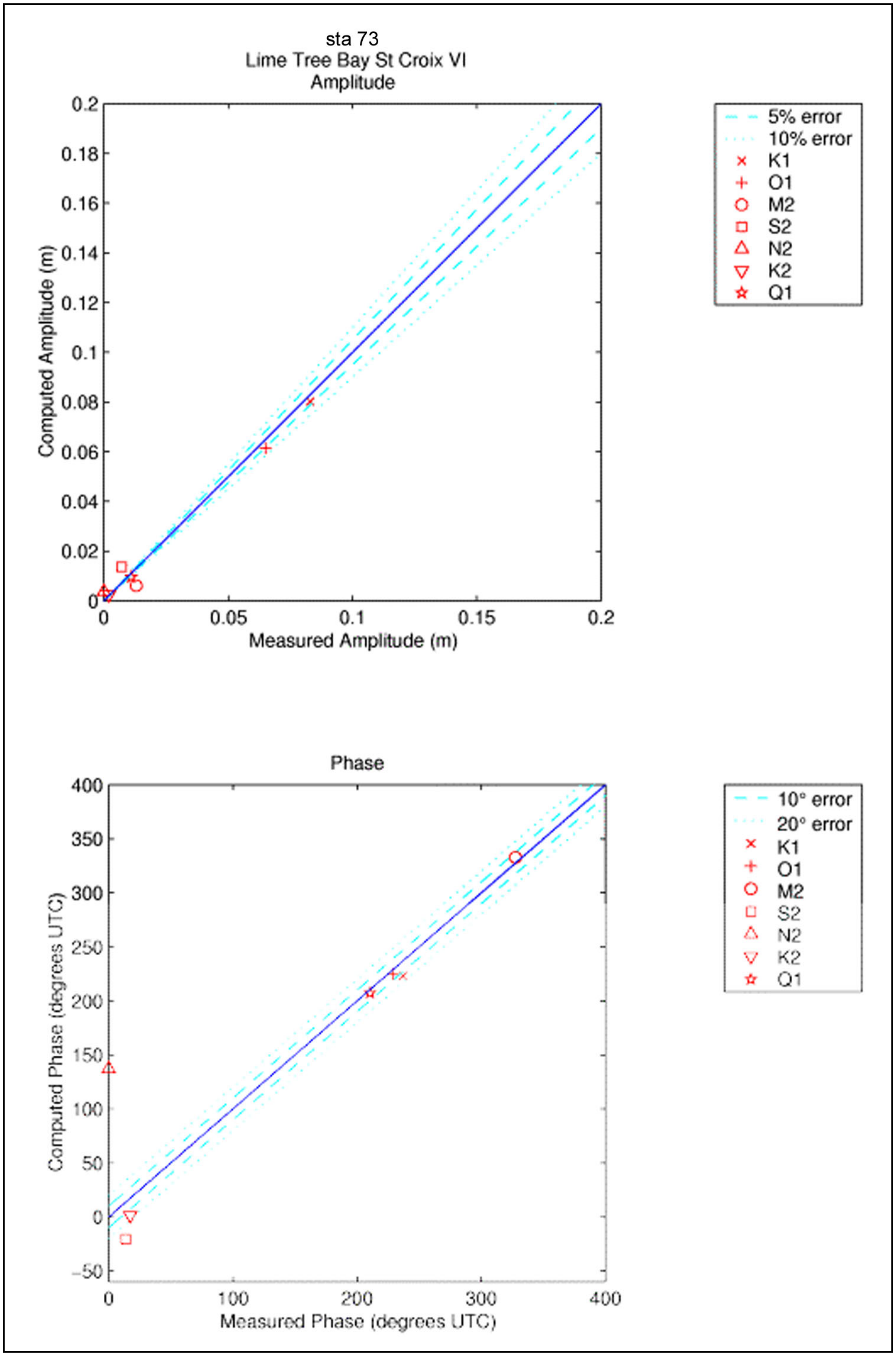

Figure 7. Computed versus measured harmonic constituents at sta 73

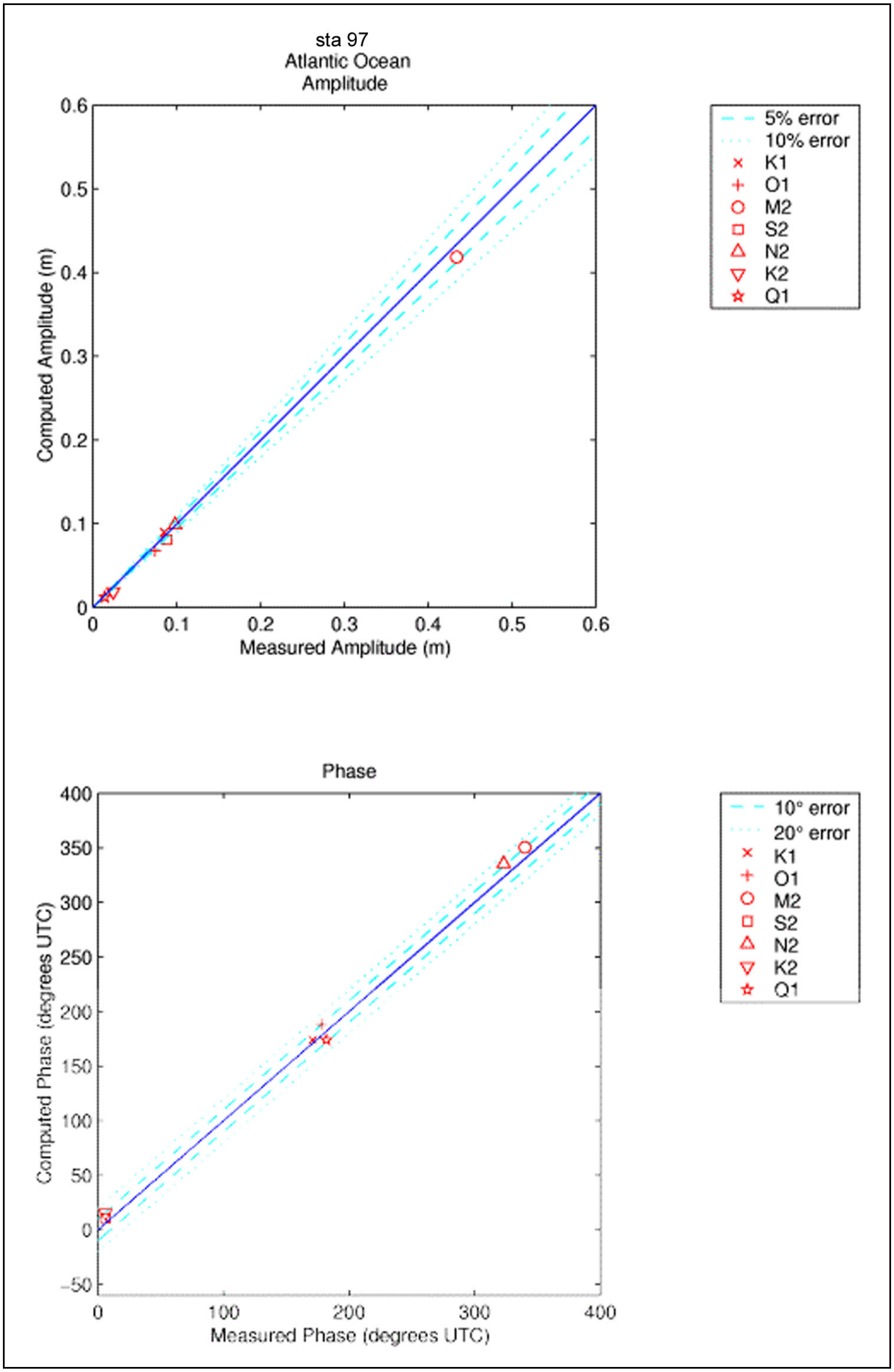

Figure 8. Computed versus measured harmonic constituents at sta 97

The accuracy of the simulated tides was further quantified by comparing the amplitude and phases of the seven astronomical constituents simulated at the 101 elevation recording stations to the actual measured field data (Mukai et al., in preparation). The computed to measured amplitude error for each constituent *j* was calculated for the entire domain, Atlantic coast, Gulf of Mexico, Caribbean Sea, and the remote stations in the Atlantic Ocean, as a proportional standard deviation. The computed to measured phase error was calculated as an absolute average error. Harmonic constituents compare to measured amplitude data to within 6 to 14 percent and to measured phase data to within 7 to 13 deg on a globally-averaged basis, with detailed values shown in Table 2 for the domain as a whole, for Atlantic Ocean coastal stations, for Gulf of Mexico stations, for Caribbean Sea stations and for Atlantic deep ocean stations. In general, comparisons to measured data are the best in the Atlantic Ocean and the worst in the Caribbean Sea. This is not entirely surprising since the bathymetric data is least accurate in the Caribbean basin, particularly on the continental shelves as well as on the Lesser Antilles ridge, which controls the Atlantic-Caribbean coupling. Overall, the dominant tidal constituents in a given basin are the most accurate. Thus the M_2, N_2 and S_2 constituents compare to measured amplitude data to within 6 to 8 percent and to measured phase data to within 4 to 8 deg on average within the Atlantic. The K_1 and O_1 constituents compare to the measured amplitude data to within 10 to 11 percent and the measured phase data to within 6 to 7 deg on average within the Gulf of Mexico.

Table 2
Eastcoast 2001 Domain and Regional Model to Measured Data Errors

Amplitude Errors, $E^{c\text{-}m}_{j\text{-}amp}$ (%)					
Constituent	**Entire Domain**	**Atlantic Coast**	**Gulf of Mexico**	**Caribbean Sea**	**Remote**
K_1	13.466	19.027	11.211	8.436	9.439
O_1	10.185	7.829	10.418	10.434	12.846
M_2	6.254	5.642	11.661	29.994	7.215
S_2	9.830	7.541	17.817	19.617	14.962
N_2	7.604	6.831	17.284	24.851	9.454
K_2	14.084	10.261	23.881	38.512	21.330
Q_1	12.809	14.601	11.321	15.134	17.057
Phase Errors, $E^{c\text{-}m}_{j\text{-}phase}$ (deg)					
Constituent	**Entire Domain**	**Atlantic Coast**	**Gulf of Mexico**	**Caribbean Sea**	**Remote**
K_1	8.07753	7.35788	6.68833	11.45950	8.12995
O_1	7.21907	7.19371	6.49900	10.95522	4.98352
M_2	9.52856	6.45435	12.66427	14.89206	6.42923
S_2	12.16547	8.36515	13.30262	19.32892	12.78745
N_2	8.93081	4.45144	12.06543	19.22187	5.39919
K_2	12.89956	12.16353	16.14971	18.84900	7.25394
Q_1	8.91849	9.09721	8.19108	11.02400	8.10176

It is noted that the computed to measured constituent error estimates in Table 2 actually include the uncertainty in the measurements. To quantify the measurement error, stations along the Atlantic coast and Gulf of Mexico with multiple measured values from both the NOS and IHO/NOAA databases were compared. Proportional standard deviations for multiple measured constituent amplitudes and absolute average errors for multiple measured constituent phases were computed (Mukai et al., in preparation). These estimates of measured data error are listed

in Table 3 for the O_1, K_1, Q_1, M_2, N_2, S_2, and K_2 tidal constituents. Overall the percent errors in amplitudes range between 3.1 and 16.1 percent, the phase differences range between 2.0 and 6.2 deg. Differences in values of tidal data between the NOS and IHO/NOAA databases can be explained by the constantly shifting bathymetry of coastal regions and of the geometry of the coasts themselves as well as by the occurrences of nontidal events. Considering measurement error estimates puts the computed-to-measured data errors into perspective. In fact, the measurement error estimates are generally half of the computed-to-measurement errors. Because the computed measurement errors include the uncertainty in the measured data, it is clear that a substantial portion of the reported computed to measured data errors originate from the errors in the measurements.

Table 3
Station Measurement Data Amplitude and Phase Errors

Amplitude Errors, $E^m_{j\text{-}amp}$ (%)			
Constituent	**Entire Domain**	**Atlantic Coast**	**Gulf of Mexico**
K_1	6.067	5.376	6.680
O_1	7.279	3.822	8.943
M_2	3.080	2.689	7.523
S_2	10.818	10.593	11.682
N_2	3.982	3.191	14.143
K_2	8.872	8.863	8.904
Q_1	16.063	11.648	18.465
Phase Errors, $E^m_{j\text{-}phase}$ (deg)			
Constituent	**Entire Domain**	**Atlantic Coast**	**Gulf of Mexico**
K_1	2.02619	1.48286	3.11286
O_1	2.89619	2.56786	3.55286
M_2	3.79857	2.54643	6.30286
S_2	4.25571	2.40500	7.95714
N_2	3.54316	3.69000	3.13200
K_2	4.50833	3.99643	6.30000
Q_1	6.15600	6.81714	4.61333

APPLICABILITY GUIDELINES FOR THE EASTCOAST 2001 DATABASE: The Eastcoast 2001 tidal database provides elevation amplitudes and phases for the, K_1, O_1, N_2, M_2, S_2, K_2, Q_1 astronomical tides and the steady state, M_4 and M_6 overtides throughout the Eastcoast 2001 domain. Most nonlinear overtides and compound tides, which tend to be significant only in shallow waters such as embayments and estuaries, were not included since the necessary level of detail was not typically included in the Eastcoast 2001 domain/grid. Furthermore the tidal database will not provide information regarding responses associated with density effects, riverine driven circulation, wind and atmospheric pressure driven events and/or oceanic currents.

Vertical and horizontal variations in density can set up steric level differences in sea surface elevation, can drive significant horizontal circulation patterns, and can cause variation in the vertical structure of the currents. These effects tend to be important in estuarine or delta systems with significant freshwater riverine inflows. Furthermore the seasonal heating of the upper layers of the ocean's surface directly drives the expansion in the upper layer water volume that is associated with a seasonal fluctuation of water level. This can be especially significant in the

Gulf of Mexico and the Caribbean Sea. It is noted that published tidal constituent data includes these seasonal sea surface expansions as long-term tidal constituents such as the Sa Solar annual and the Ssa Solar semiannual constituents. From a tidal hydrodynamics perspective these long-term constituents (with periods of a year and half a year respectively) are of astronomical origin and should appear as weak tides. They may also be generated through nonlinear interactions that lead to extremely weak responses. Nonetheless, in harmonically-decomposed measured field data, these constituents can appear as significant constituents since the driving radiational heating process is also an annual event. In the Gulf of Mexico, the Sa and Ssa elevation constituents can be almost as large as the dominant diurnal tides while current responses are much smaller due to the long-term period associated with these constituents. Thus it is emphasized that the Eastcoast 2001 computations are entirely barotropic and do not include any of these density effects.

Rivers were not included in the Eastcoast 2001 tidal database calculations. The barotropic pressure gradient and mass input effects of the river will be important in the immediate vicinity of the river outlet and will diminish away from the river outlet. Wind driven and/or atmospheric pressure driven effects such as coastal setup and storm surge and any basinwide modes that may be set up by these processes are also not included in the database. These effects can be significant on the shelf as well as within bays and estuaries. Major oceanic circulation patterns such as the Gulf Stream and the associated loop currents and other eddies, which are shed from it, are not included in the database. These currents tend to reside off the shelf in deep ocean waters but can be associated with fast flows in the 1 to 2 m/sec range.

Finally the local accuracy of the Eastcoast 2001 tidal computations will be affected by the accuracy of the geometry and bathymetry locally defined in the WNAT-based Eastcoast 2001 grid. Geometric and bathymetric inaccuracies in the Eastcoast 2001 grid will especially affect the accuracy of the currents. Obviously a missing estuary or island or inaccurate bathymetry will greatly influence the database computations.

USAGE GUIDELINES FOR EASTCOAST 2001 DATABASE: The Eastcoast 2001 tidal constituent database can be applied anywhere within the defined WNAT domain. However, the prevailing hydrodynamics in a specific region will determine how accurately the currents will be predicted. If the surface elevation response and currents are indeed dominated by astronomical tides, then the database will provide an excellent prediction of the response. A good estimate of the accuracy of the Eastcoast 2001 tides can be obtained by examining the basinwide computed to measured error estimates in Table 2 and the measurement error estimates in Table 3 or even more accurately by finding the nearest measurement station or stations in Figure 4 and examining the plotted station computed to measured constituent amplitudes and phases. Furthermore how accurately the Eastcoast 2001 grid and bathymetry describe the region of specific interest influences the accuracy and appropriateness of applying database values.

For locations that are tidally dominated and for which the Eastcoast 2001 grid accurately describes both local geometry and bathymetry, the database can be directly applied to extract tidal elevations and currents. Because the seven astronomical and three overtide constituents are computed at every node and are defined within the framework of a finite element grid, values at any point within the domain can be readily interpolated from the nodal values within which the

point lies. An extraction program, *tides_v1.06.f*, together with the Eastcoast 2001 finite element grid file accompany the tidal database. A required input file, *tides.in*, supplies a list of coordinates to the extraction program to produce an output of harmonic constituent elevation amplitude and phase at the specified location(s). A time-history of response can then be readily Fourier synthesized. For example a time-history of water-surface elevation can be computed as:

$$\zeta(x,y,t) = \sum A_i(x,y) f_i(t_0) \cos\left[\frac{2\pi}{T_i}(t-t_0) + V_i(t_0) - \Psi_i(x,y)\right]$$

$A_i(x,y)$ and $\Psi_i(x,y)$ are the amplitude and phase, respectively, at the location (x,y) of interest for constituent i, which are provided by the Eastcoast 2001 tidal database. The periods T_i in seconds for each of the 10 constituents included in the database are presented in Table 4. It is important to specify frequencies precisely, at least to eight significant figures. The nodal factor $f_i(t_0)$ and the equilibrium argument, $V_i(t_0)$, relative to reference time t_0 can be computed using program *tide_fac.f* and is also provided with the Eastcoast 2001 database.

Table 4
Frequencies and Periods for Eastcoast 2001 Response Constituents

Constituent	Frequency (radians/sec)	Period (hr)
Steady	0.000000000000000	∞
K_1	0.00007292115836	23.93446966
O_1	0.00006759774415	25.81934167
M_2	0.00014051890251	12.42060122
S_2	0.00014544410433	12.00000000
N_2	0.00013787969949	12.65834826
K_2	0.00014584231720	11.96723479
Q_1	0.00006495854113	26.86835668
M_4	0.00028103780502	6.210300610
M_6	0.00042155670753	4.140200408

In locations and/or at times where the hydrodynamics is not tidally dominated and/or the Eastcoast 2001 grid does not provide sufficient geometric and/or bathymetric detail, a regional model that interfaces with the Eastcoast 2001 model will lead to a better representation of regional flows. Some examples of cases where this may be appropriate include: (a) bays or estuaries not included in the grid; (b) shallow nonlinearly-dominated inlets or embayments; (c) coastal and/or estuarine regions barotropically and/or baroclinically influenced by a significant riverine discharge; (d) combined wind- and tidally-driven circulation on a shelf. The basic idea is to construct a domain/grid that extends onto or beyond the shelf within the Eastcoast 2001 domain. The open ocean boundary is then forced using the tidal constituent data from the Eastcoast 2001 tidal data base. The defined domain may also include additional regional detail in geometric and bathymetric definition, may include additional forcing functions on select boundaries or within the domain, and/or may include additional terms in the governing equations.

The regional model open ocean boundary should be placed away from the region of immediate interest, and its exact position and shape depends on the application. In no case should the boundary be placed at the mouth or entrance to an embayment of interest. The tidal constituents

on the open ocean boundary nodes of the regional model are extracted in the same way as a simple point location. It may be necessary to add an additional forcing component to the boundary elevation and/or radiation forcing function to account for additional interior domain processes and forces. In the development of a regional model it is also recommended that the bathymetry along the open boundary match the bathymetry of the Eastcoast 2001 grid. This will help ensure that the boundary condition extracted from the Eastcoast 2001 database is physically consistent with the regional model. Failure to match bathymetries along the regional model open boundary can lead to unrealistic gyre formation and/or instabilities in the regional model computations. The bathymetry can depart from that comprising the Eastcoast 2001 grid away from the open boundary area.

AVAILABILITY: The Eastcoast 2001 database is available through the Surface-Water Modeling System (SMS) and the Coastal Inlets Research Program Web site at *http://cirp.wes.army.mil/cirp*. For information about the Surface-Water Modeling System and inlet applications, please contact Mr. Mitch Brown (Voice: 601-634-4036, e-mail *Mitch.E.Brown@erdc.usace.army.mil*). In addition, an html version of this CHETN is available with hotlinks to plots of each station on the CIRP Web site at *http://cirp.wes.army.mil/cirp*.

ADDITIONAL INFORMATION: Questions about this technical note can be addressed to Dr. Joannes J. Westerink (Voice: 219-631-6475, e-mail: *jjw@photius.ce.nd.edu*) or Ms. Mary Cialone (Voice: 601-634-634-2139, e-mail: *Mary.A.Cialone@erdc.usace.army.mil*). Information on the ADCIRC hydrodynamics model can be found at: *http://www.unc.edu/depts/marine/C_CATS/adcirc*. For information about the Coastal Inlets Research Program, please contact the Program Technical Leader, Dr. Nicholas C. Kraus (Voice: 601-634-2016, e-mail: *Nicholas.C.Kraus@erdc.usace.army.mil*). This technical note should be cited as follows:

> Mukai, A.Y., Westerink, J. J., and Luettich, R. A.. (2001). "Guidelines for using Eastcoast 2001 database of tidal constituents within Western North Atlantic Ocean, Gulf of Mexico and Caribbean," Coastal and Hydraulics Engineering Technical Note CHETN-IV-40, U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://chl.wes.army.mil/library/publications/chetn/*

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